Experimental Study of β and α

1. A brief reminder of the CKM triangle
2. Measurements of $\sin 2\beta$
3. Details of the CDF measurement
4. Plans and Prospects for
   - $\sin 2\beta$
   - $\sin 2\alpha$
5. Summary

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The CKM Triangle

Unitary CKM matrix governs weak decay of quarks

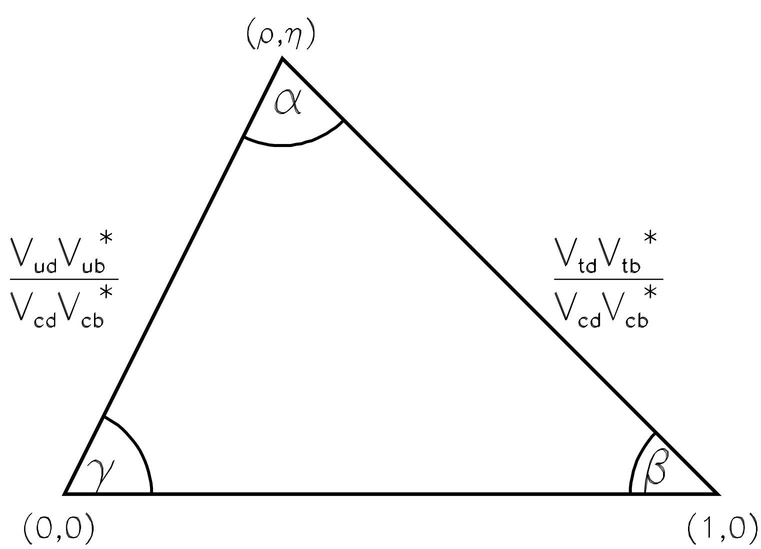
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation:

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

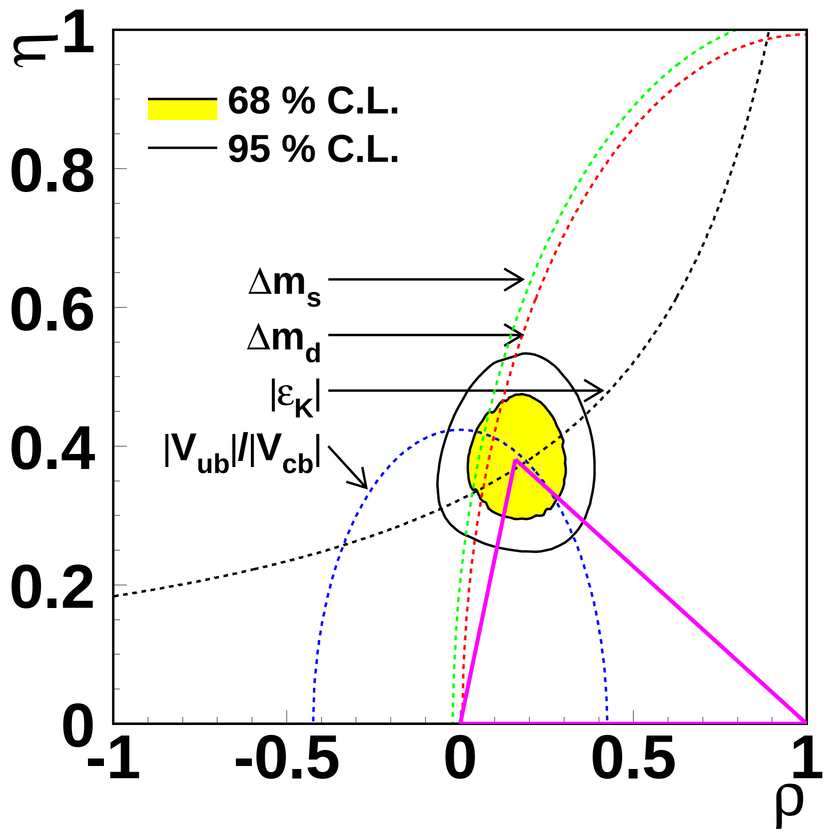
Unitarity $\rightarrow V^\dagger V = 1$ gives:

$$V_{tb}^* V_{td} + V_{cb}^* V_{cd} + V_{ub}^* V_{ud} = 0$$



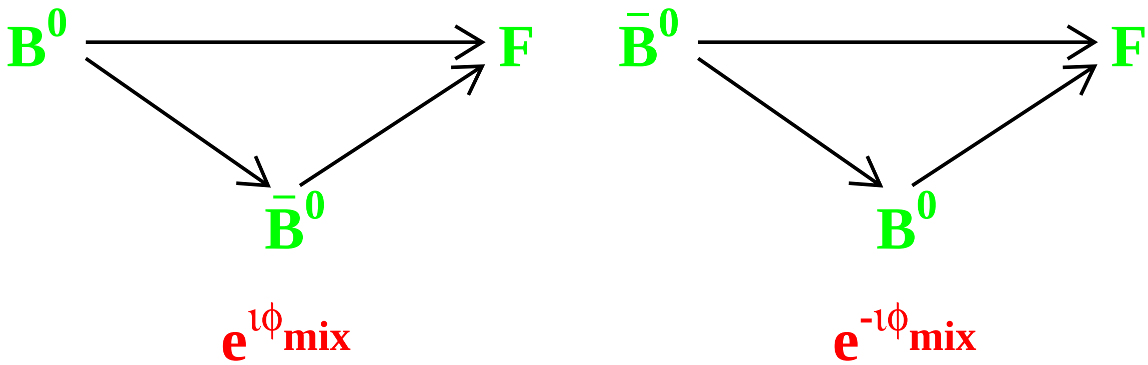
$$\alpha = \arg\left(\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \beta = \arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Constraints on β from CKM Matrix



Experiment	sin 2β	Reference
CKM model fit	0.75 ± 0.09	S. Mele, PRL**59**, 113011 (99)

The CP Asymmetry

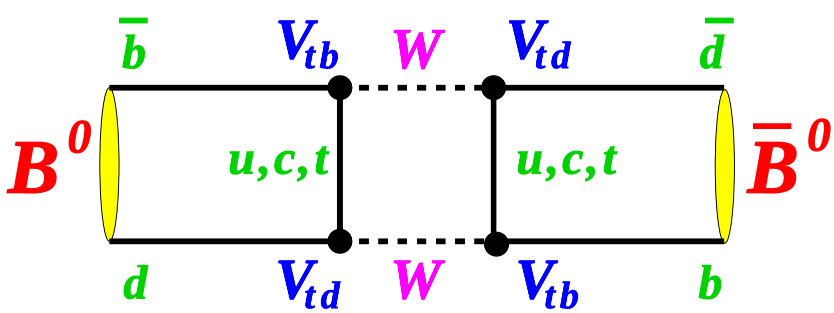


- Results in:

$$\frac{dN}{dt}(B^0 \rightarrow J/\psi K_S^0) \sim 1 - \sin\ 2\beta\ \sin\ \Delta m t$$

$$\frac{dN}{dt}(\bar{B}^0 \rightarrow J/\psi K_S^0) \sim 1 + \sin\ 2\beta\ \sin\ \Delta m t$$

- CP phase easily seen in CKM matrix element V_{td}



- B^0 and $\bar{B}^0$ produced at equal rates develop asymmetry:

$$\begin{aligned} A_{CP}(t) &= \frac{\frac{dN}{dt}(\bar{B}^0 \rightarrow J/\psi K_S^0) - \frac{dN}{dt}(B^0 \rightarrow J/\psi K_S^0)}{\frac{dN}{dt}(\bar{B}^0 \rightarrow J/\psi K_S^0) + \frac{dN}{dt}(B^0 \rightarrow J/\psi K_S^0)} \\ &= \sin\ 2\beta\ \sin\ \Delta m t \end{aligned}$$

Experimental Considerations

- Production mechanism can be important
  - At hadron collider $b\bar{b}$ not produced in coherent state
    - time averaged asymmetry does not vanish
    - time dependent asymmetry msmt. improves precision
  - At B factory $B^0\bar{B}^0$ produced in coherent P-wave state
    - CP asymmetry only builds after first B meson decays
    - Must measure asymmetry to access CP information
- Both require tagging of original B^0 flavour to see asymmetry

$$A_{CP}^{obs} = \mathcal{D} A_{CP}$$

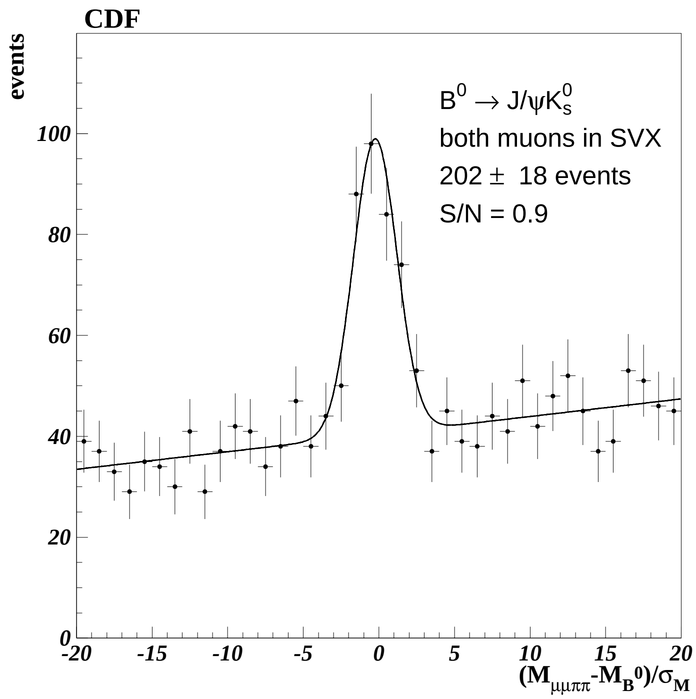
- $\mathcal{D}$ is the "tagging dilution"
  - $\mathcal{D} = (N_r - N_w)/(N_r + N_w)$
  - $N_r(N_w)$ are the number of right (wrong) tags
  - Constrain $\mathcal{D}$ from data
- Precision on sin 2β given by

$$\delta \sin\ 2\beta \approx 0.47 \frac{1}{\sqrt{\epsilon \mathcal{D}^2}} \sqrt{\frac{S+B}{S^2}}$$

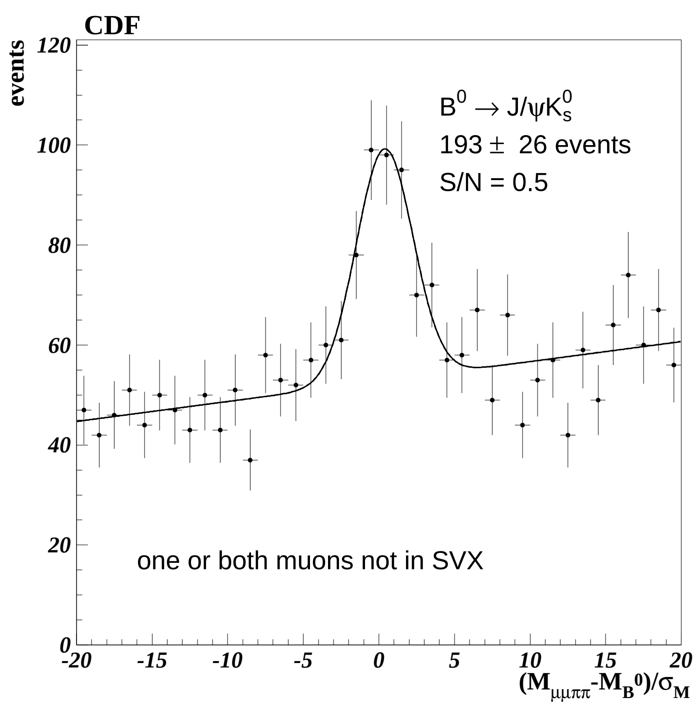
  - ϵ is fraction of events with a tag
  - S is number of signal events
  - B is number of background events

CDF Data Sample

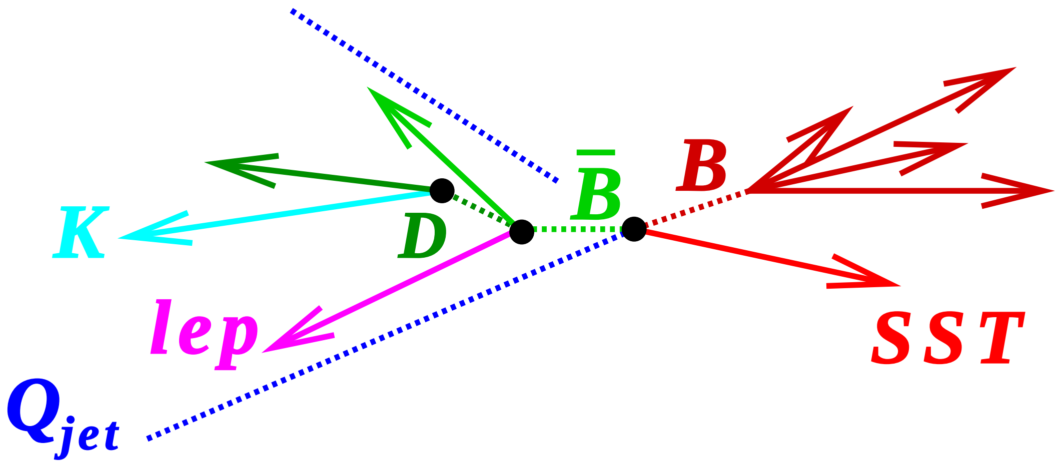
Both J/ψ muons have SVX information (≈ 200 events)



One or both J/ψ muons lack SVX information (≈ 200 events)



Methods for Tagging Initial B^0 Flavour



Determine the flavour (B^0 vs $\bar{B}^0$) at time of production

Opposite-Side Tagging

- Charge of opposite-side jet (JETQ)
- Soft e or μ tag from semi-leptonic decay of opposite B (SLT)

Same-Side Tagging

- Same-side SVX and non-SVX pion tagging (SST)

Jet Charge Tagging (JETQ)

- Opposite-side b quark can fragment into any B meson
- Identify flavour of b quark through charge of opposite jet
- Use a variant of *JADE* track cluster algorithm
  - optimised for low p_t jets
- Weight individual track charges by
  - transverse momentum
  - impact parameter ($T_i \approx 0$ for displaced tracks)

$$Q_{jet} = \frac{\sum q_i p_i (2 - T_i)}{\sum p_i (2 - T_i)}$$

  - $Q_{jet} > 0.2 \rightarrow b$
  - $Q_{jet} < -0.2 \rightarrow \bar{b}$
  - $|Q_{jet}| < 0.2 \rightarrow$ **no tag**

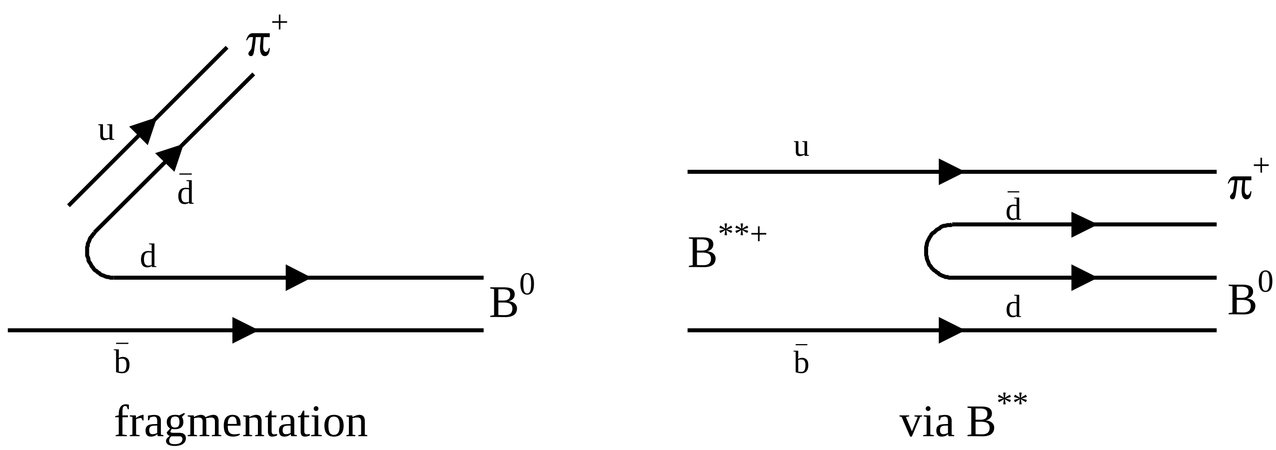
- 40% of $J/\psi K_S^0$ have a jet charge tag
- $\mathcal{D} = 0.235 \pm 0.069$ calibrated on $J/\psi K^{\pm}$ sample

Soft Lepton Tagging (SLT)

- Identify flavour of opposite B hadron through $b \to l\nu X$ decay
- Semileptonic branching ratio leads to $\approx 6\%$ efficiency
- Electron selection
  - Central track ($p_t > 1$ GeV/c) matched to EM shower
- Muon selection
  - Central track ($p_t > 2$ GeV/c) matched to muon stub
- When present: $\mathcal{D} = 0.625 \pm 0.146$ on $J/\psi K^{\pm}$ sample

Same Side Tagging (SST)

- Opposite tagging limited
  - other b is central only 50% of the time
  - if other b is B^0 or B_s^0 it mixes
- Exploit correlated fragmentation on same side



- Use semi-leptonic B meson decays to calibrate SVX sample

$$\mathcal{D} = 0.166 \pm 0.022$$

- Use $B^\pm \to J/\psi K^\pm$ sample to calibrate non-SVX sample

$$\mathcal{D} = 0.174 \pm 0.036$$

Summary of Flavour Tagging

Tagger	Events	efficiency (ϵ)	Dilution ($\mathcal{D}$)
SST	SVX	35.5 ± 3.7 %	16.6 ± 2.2 %
SST	non-SVX	38.1 ± 3.9 %	17.4 ± 3.6 %
SLT	all	5.6 ± 1.8 %	62.5 ± 14.6 %
JETQ	all	40.2 ± 3.9 %	23.5 ± 6.9 %

Tagging algorithms all contribute similar statistical power:

Tagger	$\epsilon\mathcal{D}^2$
SST	2.1 ± 0.5 %
SLT	2.2 ± 1.0 %
JETQ	2.2 ± 1.3 %

Expect combination of algorithms (with correlations) to give:

$$\epsilon\mathcal{D}^2 = 6.3 \pm 1.7\%$$

~ 400 $J/\psi K_s^0$ events equivalent to ~ 25 perfectly tagged events

Combining Different Taggers

- Example: SST ($\mathcal{D} = 16.6\%$) and JETQ ($\mathcal{D} = 21.5$ %)
  - If the taggers agree:

$$\begin{aligned} \mathcal{D}_{eff} &= (\mathcal{D}_{\mathsf{SST}} + \mathcal{D}_{\mathsf{JETQ}})/(1 + \mathcal{D}_{\mathsf{SST}}\mathcal{D}_{\mathsf{JETQ}}) \\ \mathcal{D}_{eff} &= (0.235 + 0.166)/(1 + 0.235 * 0.166) = 39\ \% \end{aligned}$$

  - If the taggers disagree:

$$\begin{aligned} \mathcal{D}_{eff} &= (\mathcal{D}_{\mathsf{SST}} - \mathcal{D}_{\mathsf{JETQ}})/(1 + \mathcal{D}_{\mathsf{SST}}\mathcal{D}_{\mathsf{JETQ}}) \\ \mathcal{D}_{eff} &= (0.235 - 0.166)/(1 - 0.235 * 0.166) = 7\ \% \end{aligned}$$

  - Sign of the tag governed by JETQ result

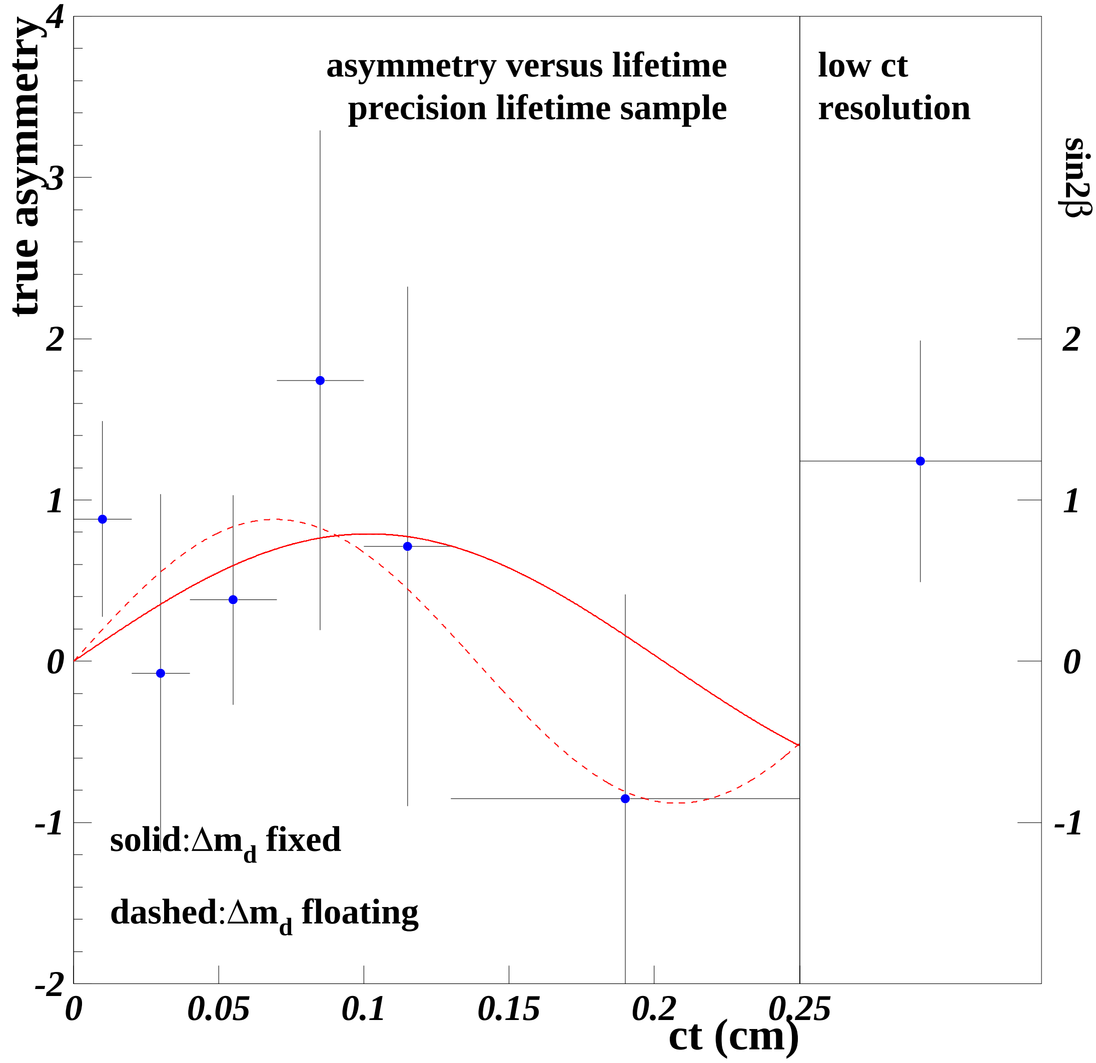
- Each event is weighted in the fit by its effective dilution

  (SLT has much higher dilution → over-rules JETQ if both present)

Overview of CDF Fit for $\sin 2\beta$

- Combine all information in maximum likelihood fit
- Allow for charge asymmetries in efficiencies and dilution
  - possible charge biases in tracking at low p_t
  - $K^{\pm}$ interaction rate differences
  - Charge asymmetric backgrounds (beampipe spallation)
- No significant asymmetries observed
- Likelihood function includes event-by-event probabilities for
  - Observed decay length
  - Reconstructed candidate mass
  - Efficiency and tagging probability
- Include constraints from other data ($B^+ \to J/\psi K^+$)
  - tagging efficiencies
  - dilutions
- Take external inputs for τ_{B^0}, Δm_d, m_B
  - Allow them to float within their errors

Result of Combined Fit



Measure

$$\sin\ 2\beta = 0.79^{+0.41}_{-0.44}(stat + syst)$$

Systematic Uncertainties

Can split off systematic uncertainty

$$\sin\ 2\beta = 0.79 \pm 0.39(stat) \pm 0.16(syst)$$

Effect	Evaluated	$\delta \sin\ 2\beta$
$\mathcal{D}$	in fit	0.16
Δm_d	in fit	0.01
τ_{B^0}	in fit	0.01
m_B	refit	0.01
charge bias	external	negligible
K_L^0 regen.	external	negligible

- Systematic dominated by $\delta\mathcal{D}$ measured in data
  - Uncertainty will scale with more data

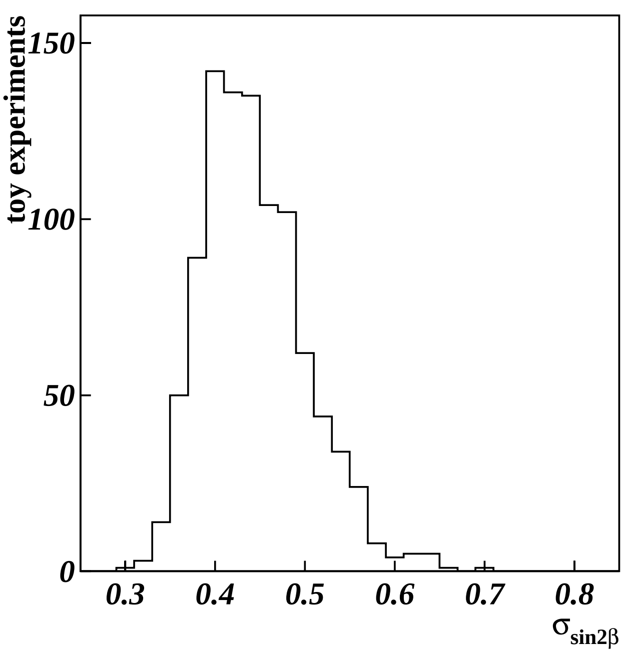
Individual Results from Sub-samples/Sub-tags

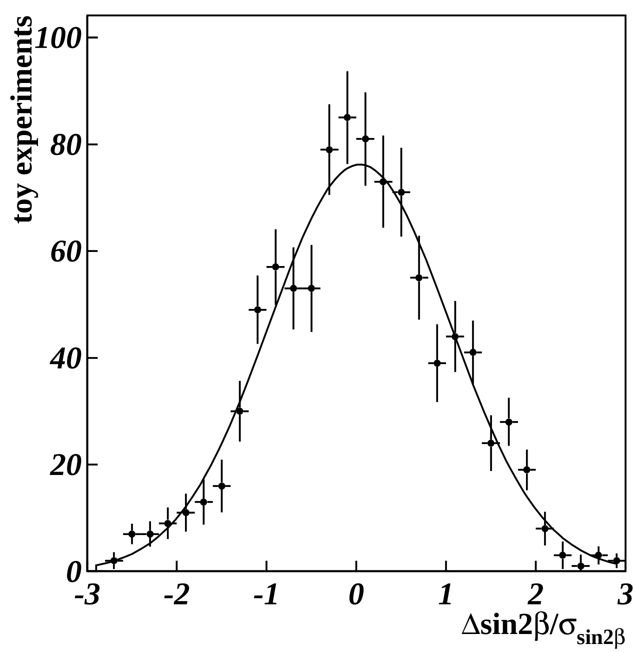
Tagger	sin 2β	Uncertainty
full fit	0.79	${}^{+0.41}_{-0.44}$
SST	2.03	${}^{+0.84}_{-0.77}$
SLT	0.52	${}^{+0.61}_{-0.75}$
JETQ	-0.31	${}^{+0.81}_{-0.85}$

- Are the three sub-results consistent?
- χ^2 of 4.6 for 2 degrees of freedom ($\mathcal{P}$ =10%)

Toy Monte Carlo Test of Fit Results

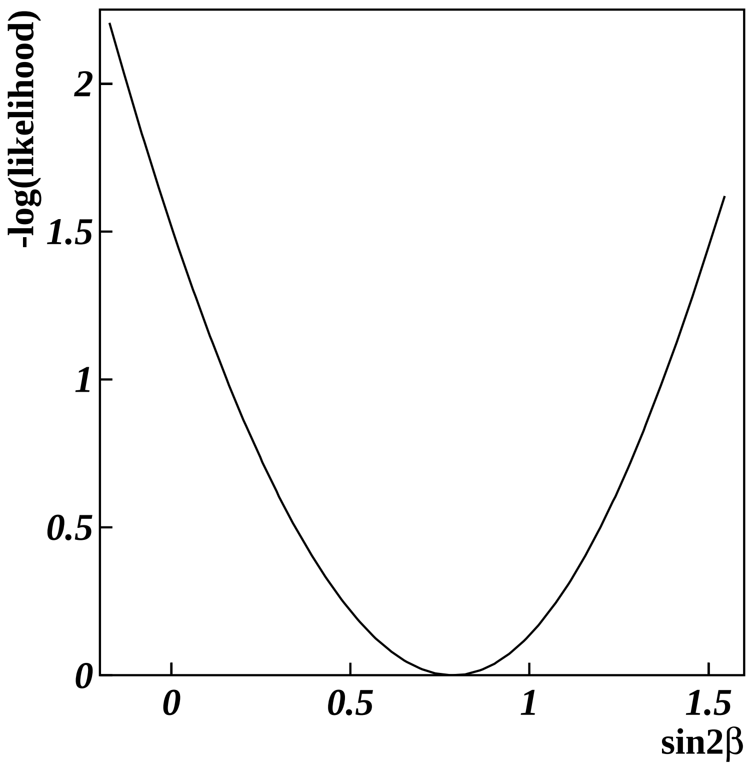
- Generate 1000 simulated "experiments" with
  - 400 $J/\psi K^0_S$ candidates 50-50 split with lifetime info
  - Backgrounds and tagging dilutions as observed
- Expected uncertainties support what we see in data (left)
- Fit returns errors consistent with fit value (right)





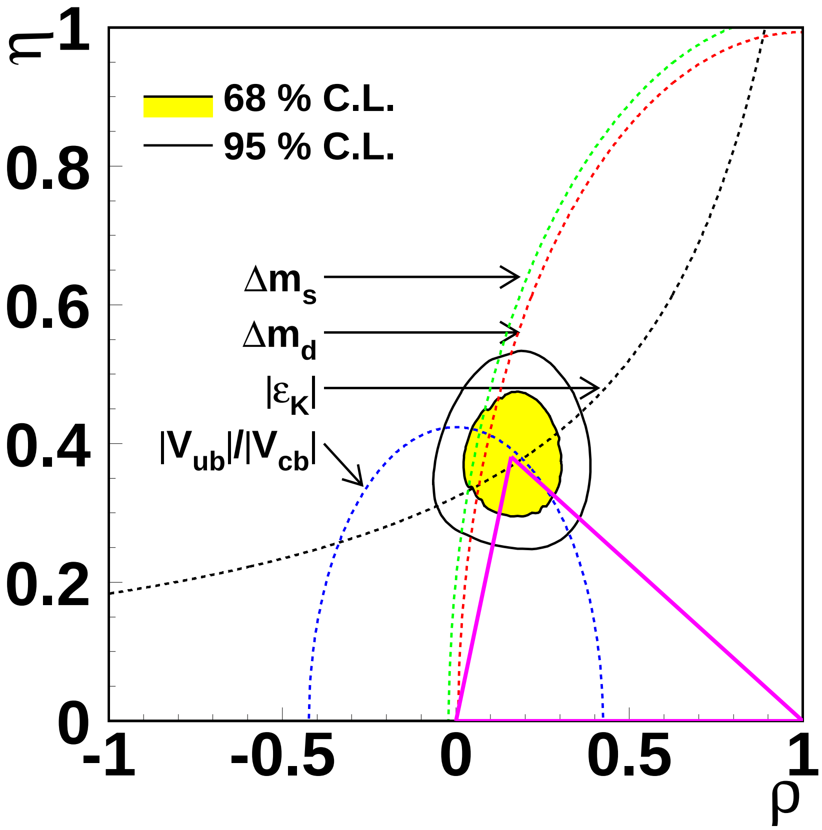
Have We Seen CP-Violation in B Decays?

Scan likelihood function:



- Feldman and Cousins frequentist limit:
  - $0 <$ sin $2\beta < 1$ at 93% CL
- Bayesian limit (assuming flat prior in sin 2β):
  - $0 <$ sin $2\beta < 1$ at 95% CL
- Assume sin $2\beta = 0$ and our uncertainty
  - Integrate Gaussian from $0.79 \rightarrow \infty$:
  - $Prob(\sin\ 2\beta > 0.79) = 3.6$ %
- Best direct evidence for CP violation in B sector

Determinations of β



Experiment	sin 2β	Reference
OPAL	$3.2^{+1.8}_{-2.0}(stat) \pm 0.5(sys)$	Euro. Phys. **C5**, 379 (98)
CDF (initial)	$1.8 \pm 1.1(stat) \pm 0.3(sys)$	PRL**81**, 5513 (98)
CDF (update)	$0.79 \pm 0.39(stat) \pm 0.16(sys)$	hep-ex/9909003
ALEPH (prelim)	$0.93^{+0.64}_{-0.88}(stat)^{+0.36}_{-0.24}(sys)$	R. Forty, this conference
Average	0.82 ± 0.38	My average
CKM model fit	0.75 ± 0.09	S. Mele, PRL**59**, 113011 (99)

Prospects for $\sin\ 2\beta$ at Tevatron

- Run II at CDF will see:
  - $\times$20 increase in luminosity (initially)
  - $\times$1.5 increase in SVX acceptance
  - $\times$2 for improved μ coverage and lower p_t for J/ψ
- Will yield 10,000 $J/\psi K_S^0$ decays for 2 fb^{-1}
- Calibration samples will grow by similar factor
- Even if no improvement in flavour tagging expect

$$\delta \sin\ 2\beta \approx 0.08$$

- Further improvements should come from
  - Addition of $J/\psi \to e^+e^-$ final states
  - Improvements to flavour tagging (TOF in CDF)
- D0 will have similar capabilities

Prospects for $\sin 2\beta$ at B Factories

- Wider range of final states being attacked

State	Babar (30 fb^{-1})	Belle (100 fb^{-1})
$J/\psi K^0_S(\pi^+\pi^-)$	0.12	0.10
$J/\psi K^0_S(\pi^0\pi^0)$	0.30	0.20
$J/\psi K^0_L$	0.15	0.12
$D^{*+}D^{*-}$	0.44	

- Expect sizeable fraction of "1 yr" datasets by next summer

- $D^{*+}D^{*-}$ will start to investigate penguin phases

Prospects for $\sin\ 2\alpha$

- $B^0 \to \pi^+\pi^-$ is simplest CP eigenstate related to α
- $\mathcal{B}(B^0 \to K^+\pi^-)$ suggests penguin amplitudes significant

- Focus first on $\pi^+\pi^-$ asymmetry ($A_{\pi^+\pi^-}$)
- Determine non-CKM contribution to relative phases later

CDF All Hadronic Trigger

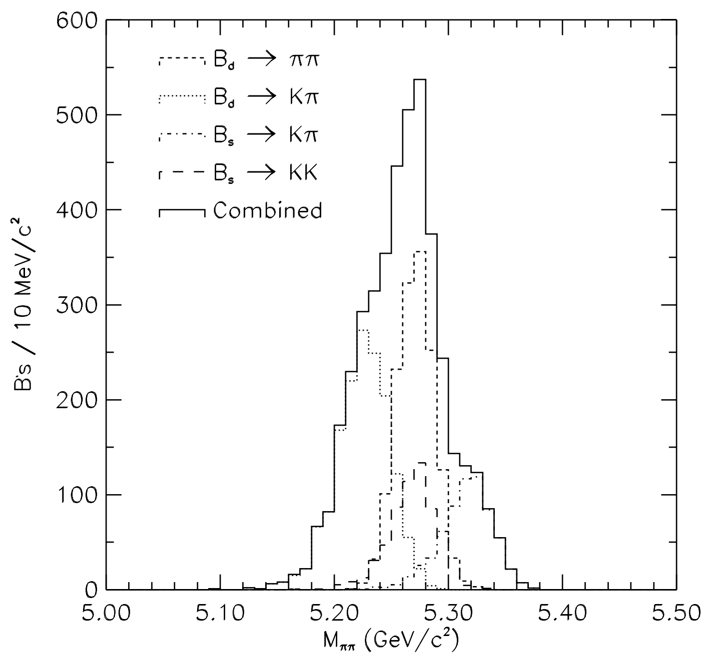
- Level 1: 2 tracks with $p_t > 2$ GeV/c
  - $\sigma_{p_t} \approx 0.02 p_t^2$
  - L1 can run up to 50 kHz deadtimeless
- Level 2: Both tracks with $d > 100\ \mu$m
  - $\sigma_d \approx 20 \oplus 40/p_t\ \mu$m
  - beamspot smaller than 25 μm
- Level 3: Use full reconstruction
  - factor of 2-5 further reduction

Luminosity	T_{cross} (ns)	$\overline{N_{p\bar{p}}}$	L1 (kHz)	L2 (Hz)
0.7×10^{32}	396	2	18	39
2.0×10^{32}	132	2	30	67
1.7×10^{32}	396	5	28	38

- Yield in 2 fb^{-1}:
  - 4000 - 7000 $B^0 \to \pi^+\pi^-$ ($\mathcal{B} = 0.5 \times 10^{-5}$)
  - 16000 - 28000 $B^0 \to K^+\pi^-$ ($\mathcal{B} = 1.9 \times 10^{-5}$)

Backgrounds to $B \to \pi^+\pi^-$

- Physics backgrounds
  - Use invariant mass to distinguish $\pi\pi$ from $K\pi$ and KK



  - dE/dx in tracking chambers
  - Will have TOF but ...
    - ∗ One sigma $\pi - K$ separation up to 1.6 GeV/c
    - ∗ Mainly for flavour tagging (an additional $\epsilon\mathcal{D}^2 \sim 2.4\%$)
  - $K\pi$ has $\cos \Delta m_d$ time dependence
- QCD light quark fakes + heavy quark combinatorics
  - studied with run I data, estimate S:B $>$ 1:4
  - subject of study at ongoing FNAL B Physics workshop
- Expect $\delta A_{\pi^+\pi^-} \sim 0.13$ (for 5000 events)

$\boxed{\textbf{Prospects for } A_{\pi^+\pi^-} \textbf{ at } B \textbf{ Factories}}$

- Wider range of modes being studied at B factories
- Asymmetry in $\pi^+\pi^-$ thoroughly studied
  - Babar $\delta A_{\pi^+\pi^-} = 0.26$ (30 fb^{-1})
  - Belle $\delta A_{\pi^+\pi^-} = 0.15$ (100 fb^{-1})
- Interpretation of asymmetry in terms of α complicated by
  - Weak phases from penguin contributions
  - Strong phases may be measured (see below)
  - Could introduce systematic of $\delta\alpha = 0.2$ (or larger)

Constraining Penguin Contributions

- Study isospin symmetry in B decays (Gronau, London)
  - $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$, $B^- \to \pi^-\pi^0$
  - $\mathcal{B}(B^0 \to \pi^0\pi^0) \sim 10^{-6} \to$ very low statistics
- Even more ambitious study $B \to \pi\pi\pi$ decays (Quinn, Snyder)
  - Dalitz analysis of modes $\rho^{\pm,0}\pi^{\mp,0}$
  - Extract 10 Amplitudes (5 tree, 5 penguin)
- Too many variables to predict outcome at this stage

Summary

- CDF has made first meaningful measurement of sin 2β
- $\sigma_{b\bar{b}}$ at hadron machines
  - allows us to compete with B factories
  - despite higher backgrounds/lower dilutions
- Experimental measurements with $\delta \sin 2\beta \approx 0.1$ on horizon
- Tools in place to attack $\pi^+\pi^-$ asymmetry
  - ideas exist to pin down penguin contributions
  - will take time/luminosity to sort out

- Should make significant progress between now and BCP4